MONTHLY WEATHER REVIEW

Editor, James E. Caskey, Jr.

VOL. 76, No. 11
W. B. No. 1531

NOVEMBER 1948

CLOSED JANUARY 5, 1949
ISSUED FEBRUARY 15, 1949

A SURFACE MICRO-STUDY OF SQUALL-LINE THUNDERSTORMS

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Manuscript received October 26, 1948

INTRODUCTION

Squall lines have long been respected for the coincidence of their passage with storms of great intensity. Usually associated with a cyclonic wave system having considerable intensity of its own, they are frequently overlooked or incorrectly located on a synoptic map because of the presence of this parent system. However, the passage of a squall line is in most cases marked by severe weather, while the surface cold front may pass later on with comparatively mild activity. Apparently, great forces exist in the squall line, but in spite of its importance, a detailed analysis of the surface weather phenomena accompanying its passage has not been possible by ordinary methods of macro-analysis. However, utilization of data from the automatic weather stations in the closely-spaced network of the U. S. Weather Bureau's Cloud Physics Project [1] at Wilmington, Ohio, has now made possible a detailed analysis of a number of squall-line thunderstorms. This paper is a presentation of the results of this micro-study of squall lines which passed over the network during an 8-month period of its operation.

Inasmuch as squall lines are frequently difficult to detect on synoptic maps it is also difficult to rigorously define them. However, for the purpose of this study, the following conditions were considered necessary and sufficient to constitute a squall line: (1) A narrow zone of activity usually parallel or nearly parallel to a surface cold front, and occurring usually some distance (e. g., 100 to 200 miles) in advance of it; (2) activity along this line characterized by thunderstorms, severe rain, brief wind shifts, gusty winds, abrupt pressure rises, and abrupt temperature falls.

In order to study the surface phenomena of squall lines critically, it was necessary to view them under magnification and in slow motion, which was made possible through the mechanically recorded data of the 55 surface weather observing stations of the Cloud Physics network. These stations were spaced in checkerboard fashion at 2-mile intervals over a rectangular area measuring 8 miles in an east-west direction by 20 miles in a north-south direction and were in continuous operation from February through September 1948. Continuous records of pressure, temperature, relative humidity, time and amount of rainfall, wind direction, and wind velocity were recorded on instruments equipped with high-speed gears and charts with expanded time scales. Since a low viscosity oil was used in the dash pots of the microbarographs, even short-interval pressure changes were not damped out. From these charts [2] data could be evaluated for any minute of the 24-hour day, and micro-synoptic surface maps could be constructed from the evaluations at frequent intervals.[1] Photographs of typical chart records from the hygrothermograph, microbarograph, rain gage, wind direction recorder, and wind velocity recorder are shown, respectively, in figures 1, 2, 3, 4, and 5.

From these graphical records for the 8 months in which the Wilmington surface network was in operation, it was possible to distinguish 11 weather situations which fulfilled the requirements of the definition of a squall line. Seven squall-line passages were analyzed in detail, with some of the results summarized in Table 1.

It goes almost without saying that thunderstorms occurred along each of these squall lines, although they could not be identified from the graphical records. However, for each of the 11 cases of squall-line passage which were analyzed, there was verification in the reports from the Clinton County Air Force Base weather station and other nearby stations that thunderstorms occurred at corresponding times.

[1] A current, independent investigation using the data on which this article is based indicates that the analysis of the micro-synoptic maps is open to some variable interpretation due to the large speed of motion of the system and the rapid fluctuations of the various meteorological elements. The speed of the system introduces difficulties in picking off from the continuous record charts the exact values of the respective elements at the time indicated, and the rapid fluctuations (particularly those of less than 5 minutes duration—see fig. 2) might be completely missed in synoptic maps spaced 5 minutes apart. However, for the purposes of this paper, the maps indicate very clearly the general features of the phenomenon discussed.—Editor.

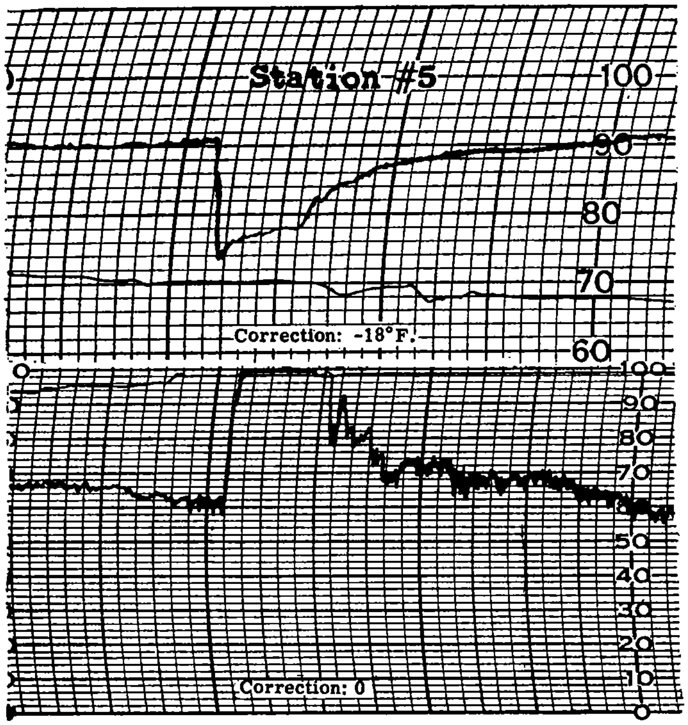

FIGURE 1.—Thermograph (upper trace) and hydrograph (lower trace) records from 1300 to 1600 E. S. T., for March 19, 1948.

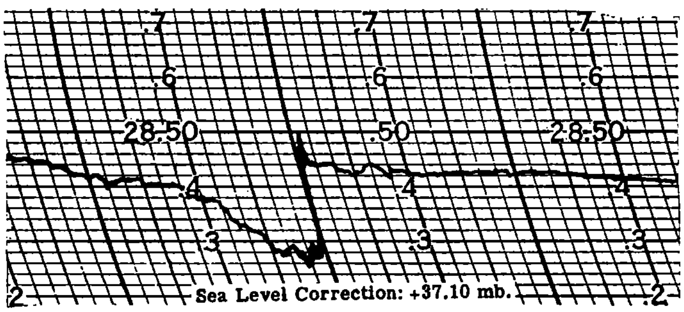

FIGURE 2.—Microbarograph record (lower trace) from 1245 to 1545 E. S. T., for March 19, 1948.

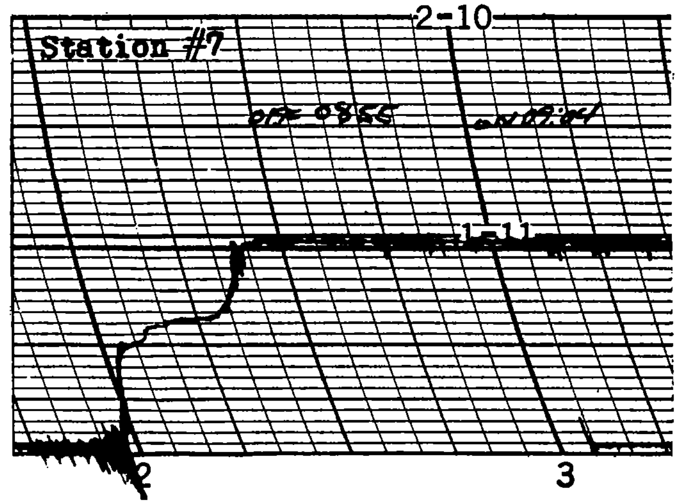

FIGURE 3.—Rain gage record from 1345 to 1515 E. S. T., for March 19, 1948.

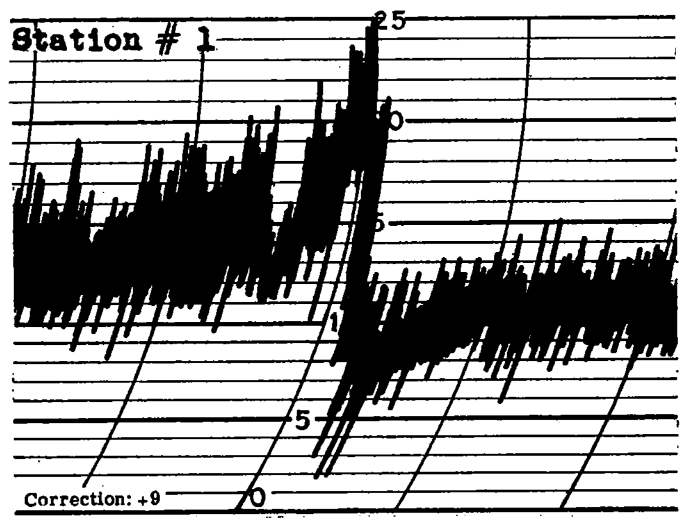

FIGURE 4.—Wind direction record from 1245 to 1445 E S. T., for March 19, 1948.

TABLE 1.—*Summary of analytical data collected from micro-analysis of seven squall-line passages*

Features of micro-study	Feb. 27	Mar. 19	Mar. 31	May 4	May 16	June 7	June 29	Average or prevailing case
	2115 E. S. T.	1400 E. S. T.	1445 E. S. T.	1615 E. S. T.	2200 E. S. T.	1930 E. S. T.	1200 E. S. T.	
GENERAL SYNOPTIC CONDITIONS								
Was squall line evident on U. S. surface map?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Was squall line associated with a cyclonic wave system?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Was squall line associated with a surface cold front?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
APPEARANCE ON MICRO-ANALYSIS								
Was squall line a uniform straight or curving line?	No	No	No	No	No	No	No	No
Did squall line move in a uniform manner?	No	No	No	No	No	No	No	No
Did micro-waves form on the squall line?	No	Yes	No	No	No	Yes	No	No
CONDITIONS IN THE MICRO-ANALYSIS								
Wind:								
Direction from which squall line moved	W.	WNW.	WNW.	W.	NW.	NW.	SSW.	WNW.
Average speed of movement (mph)	40	45	35	40	45	45	40	40
Did wind shift appreciably upon squall-line passage?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Was a peak gust associated with squall-line passage?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maximum value of peak gust (mph)	46	78	52	43	56	51	70	56
Pressure:								
Maximum gradient behind squall line (mb/mi)	1.0	2.0	1.0	1.3	1.7	1.2	1.0	1.3
Maximum isallobaric rise behind line (mb/5 min)	2.6	5.6	2.0	2.4	3.0	2.4	2.4	2.9
Did a micro-high or micro-ridge follow the squal line?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Was a micro-low present on squall line?	No	Yes	No	No	No	Yes	No	No
Precipitation:								
Did precipitation occur ahead of squall line?	No	No	No	Yes	No	Yes	No	No
Did precipitation occur behind squall line?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maximum rainfall (in/5 min)	0.35	0.60	0.22	0.40	0.17	0.48	0.36	0.37
Duration of "severe" rain (minutes)	5–10	10–15	15–20	10–15	15–20	30–35	15–20	16
Duration of total rainfall (minutes)	60–90	25–30	40–45	45–60	25–30	40–45	45–60	45
Temperature:								
Did temperature fall behind the squall line?	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Did temperature rise behind the squall line?	Yes	No	No	No	No	No	No	No
Maximum amount temperature rose or fell (°F.)	4	17	16	4	12	12	18	15

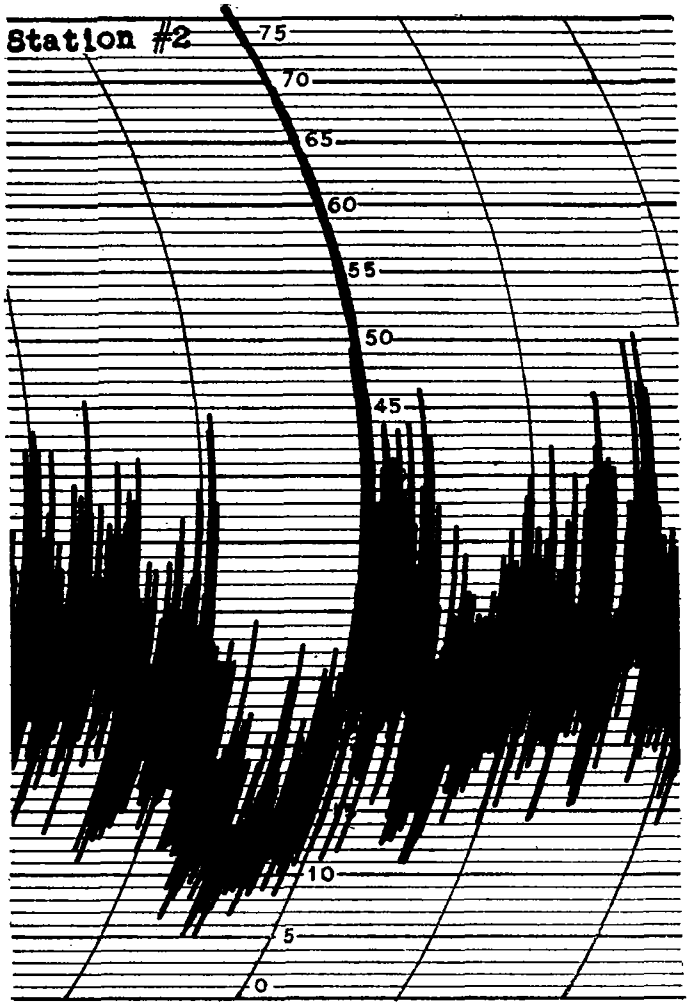

Figure 5.—Wind speed record for 1245 to 1445 E. S. T., for March 19, 1948.

METHOD OF MICRO-ANALYSIS

In the interest of analyzing the surface data in slow motion, a series of micro-synoptic surface maps was prepared for each squall-line passage, with the maps in each series drawn for successive 5-minute intervals. In the interest of magnification, the maps used were on a scale of ½ inch equal to 1 mile.[2] Data were plotted on them in the usual manner for synoptic maps, with the following exceptions: (a) isallobaric characteristics and amounts were for 5-minute intervals instead of for the customary 3-hour interval, since pressure changes occur so rapidly along the squall line that the longer interval did not give a descriptive tendency; (b) rainfall intensities and amounts were for 5-minute intervals. Isobars were drawn for each whole millibar, and isallobars were drawn for each whole millibar of change per 5 minutes. The leading edge of squall-line activity was indicated as a series of broken, dash-dot lines. Areas of high and low pressure were labeled, and regions where rain was falling were shaded.

[2] Reproductions are on the scale of ¼ inch equal to 1 mile, due to the necessity of reducing them in size for inclusion in this booklet.

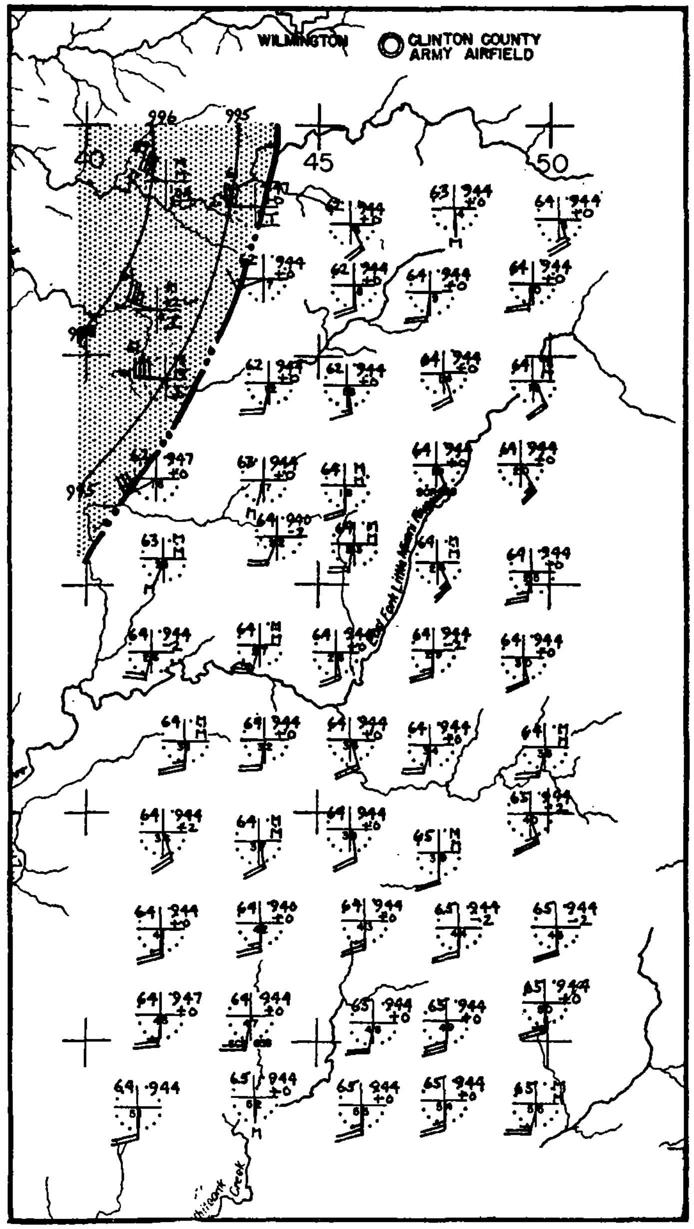

Figure 6.—Surface micro-synoptic map for Wilmington Ohio area, 1440 E. S. T., March 31, 1948.

Examples of these micro-synoptic surface maps are shown for two squall-line passages. The series for the typical one which occurred on March 31, 1948, is reproduced in figures 6, 7, and 8. In addition, a section of the regular United States synoptic map [3] for 1330 E. S. T. of the same day is reproduced in figure 9 to indicate the general synoptic pattern for the Wilmington (ILN), Ohio, area. The second series represents the unusually severe squall-line passage of March 19, 1948 (figs. 10, 11, and 12). Property damage of considerable amount resulted from this storm. Figure 13 is included to show a section of the regular United States synoptic map [3] for 1330 E. S. T. of the same day, indicating the general synoptic pattern for the area.

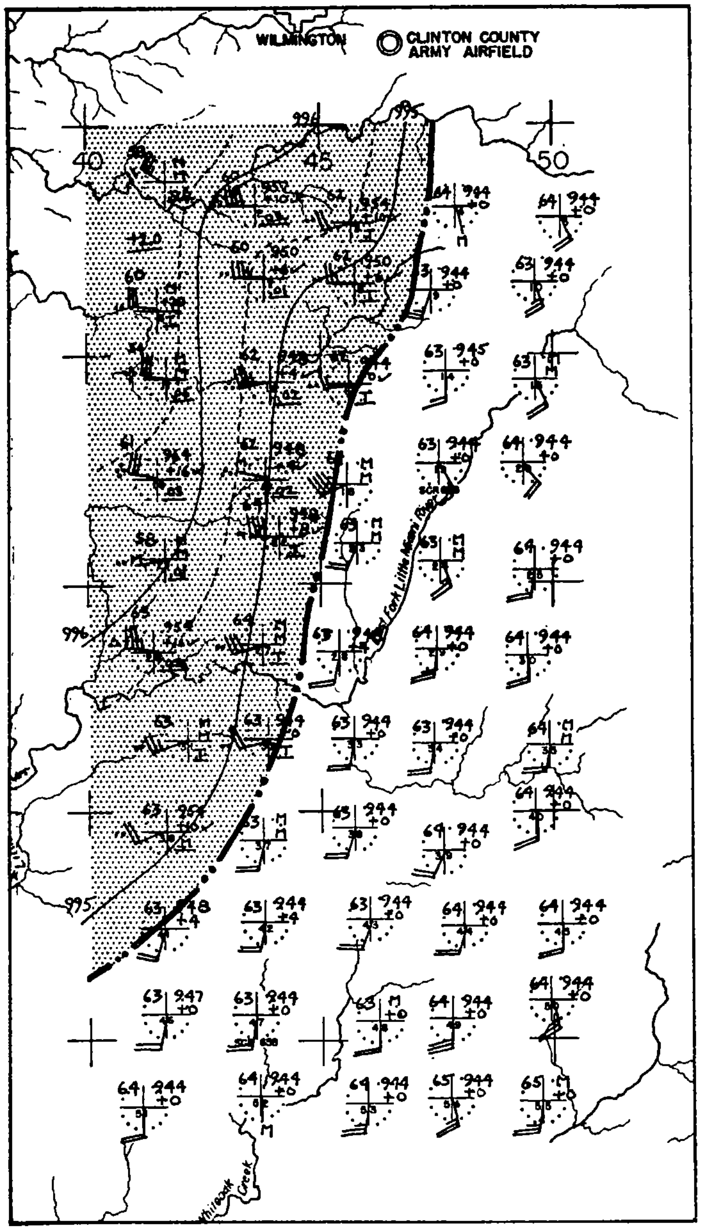

FIGURE 7.—Surface micro-synoptic map for Wilmington Ohio area, 1445 E. S. T., March 31, 1948.

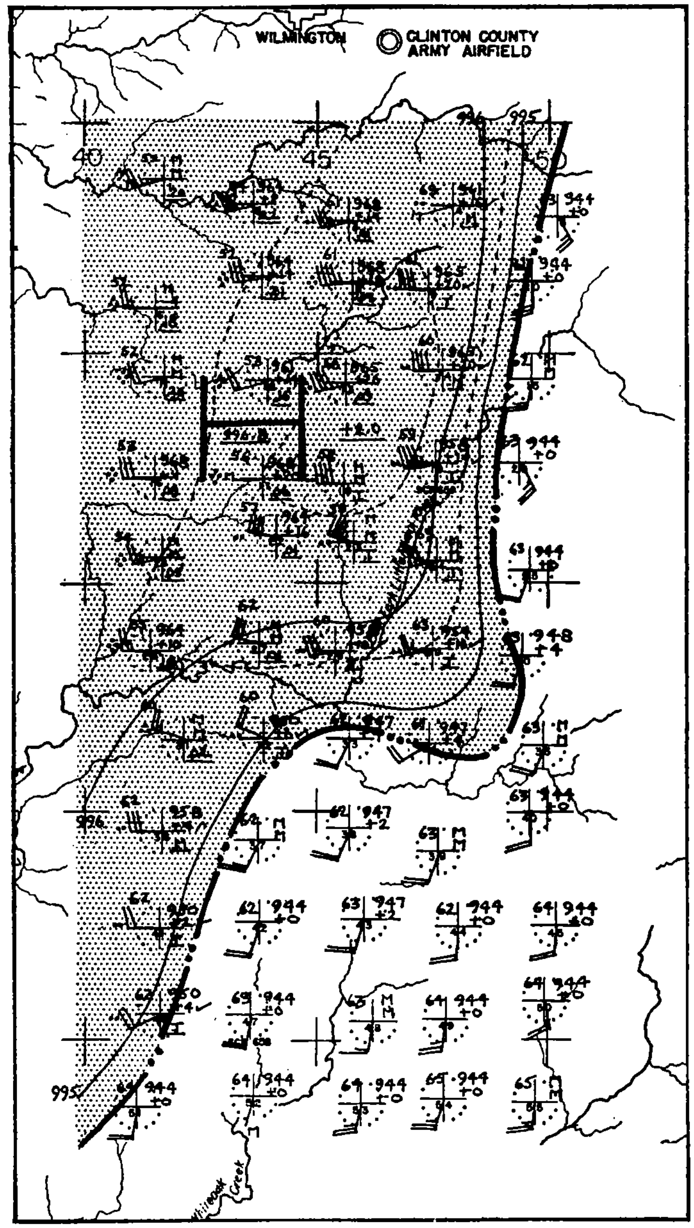

FIGURE 8.—Surface micro-synoptic map for Wilmington Ohio area, 1450 E. S. T., March 31, 1948.

RESULTS OF MICRO-STUDY

From the study of the 11 recognizable squall-line passages and the micro-anylysis of 7 of them, a number of generalizations have been made and are presented in the following paragraphs.

DIURNAL AND SEASONAL OCCURRENCE

From the graphical records it was found that all of the squall-line passages occurred between the hours of 0600 and 2200 E. S. T. and none occurred during the early morning hours. Of the 7 which were analyzed, all occurred between the hours of 1200 and 2200 E. S. T. Therefore, although an insufficient number of cases were studied to constitute proof of the statement, it appears that severe storms associated with squall-line passages in the Ohio region are most likely to occur during afternoon and evening hours.

These passages were well distributed throughout the period from February 27 to June 29, except that none occurred during April. The seven which were analyzed in detail occurred on February 27, March 19, March 31, May 4, May 16, June 7, and June 29. The other four occurred on March 2, March 15, May 2, and June 6. No recognizable ones occurred after June 29. In other words, all of the squall-line passages which were identified occurred in late winter, spring, and early summer.

RELATION TO FRONTAL SYSTEM

It is not within the scope of this paper to theorize on the origin of squall lines nor to speculate on their upper-air structure. However, some mention can be made in regard to the recent surface history of the 11 which were studied. In all cases except one the squall line was associated with a major cyclonic wave system which was present on the surface synoptic map; usually the line of activity appeared at some distance in advance of the surface cold front. However, micro-analysis of the line of activity yielded similar results in all cases, regardless of its relation to the general synoptic situation.

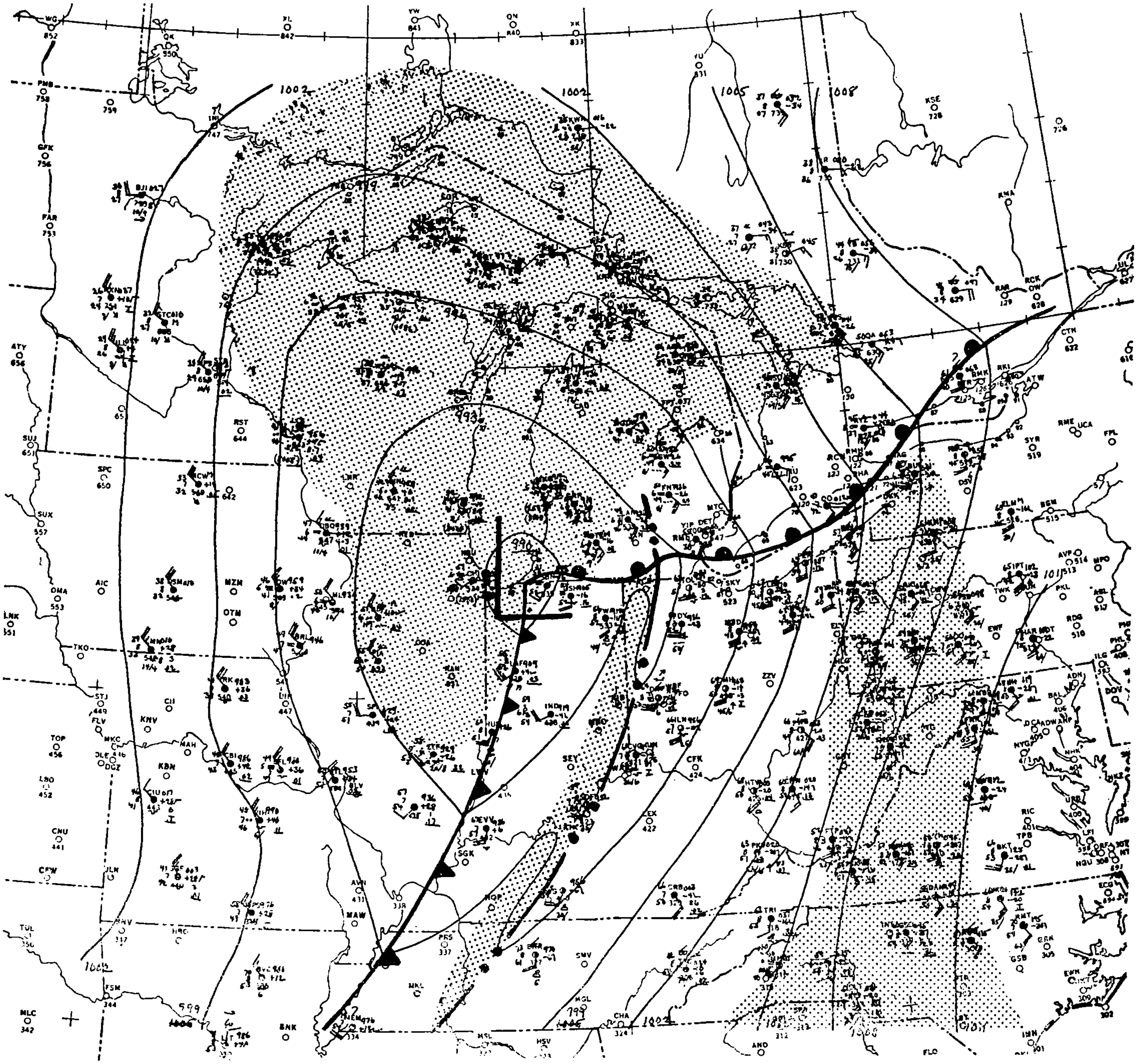

FIGURE 9.—Section of United States surface synoptic map for 1330 E. S. T., March 31, 1948.

METEOROLOGICAL FEATURES OF SQUALL LINES

Pattern of the squall line.—On regular surface synoptic maps, squall lines are indicated as straight or gently curving lines moving uniformly across the map. From the micro-analysis, it was determined that this is not representative. On the micro-synoptic maps, none of the seven cases of squall lines were represented by straight lines, nor did the lines of activity move uniformly across the network on the series of maps for each case. Small sections of the line accelerated or slowed down; surges occurred here and there. Although the lines were continuous and sharply defined, their progress was jumpy.

Formation of micro-lows.—In two of the seven cases which were analyzed, it was found that small low centers, or micro-lows, developed along the squall lines. At the center of the micro-low, the squall line developed a small perturbation, or micro-wave, which in one case actually occluded and then dissipated. In the other case (storm of March 19, 1948) it flattened out when the micro-low containing it filled. Property damage in the latter storm was considerable, with roofs ripped from some buildings, others blown down, trees blown over, and a covered bridge damaged. The damage was greatest along the path traversed by this micro-wave. Again, there was an insufficient number of cases to make any generalization concerning the formation of these micro-waves, but it is likely that they form from time to time along squall lines and last probably no more than 30 minutes before they disappear.

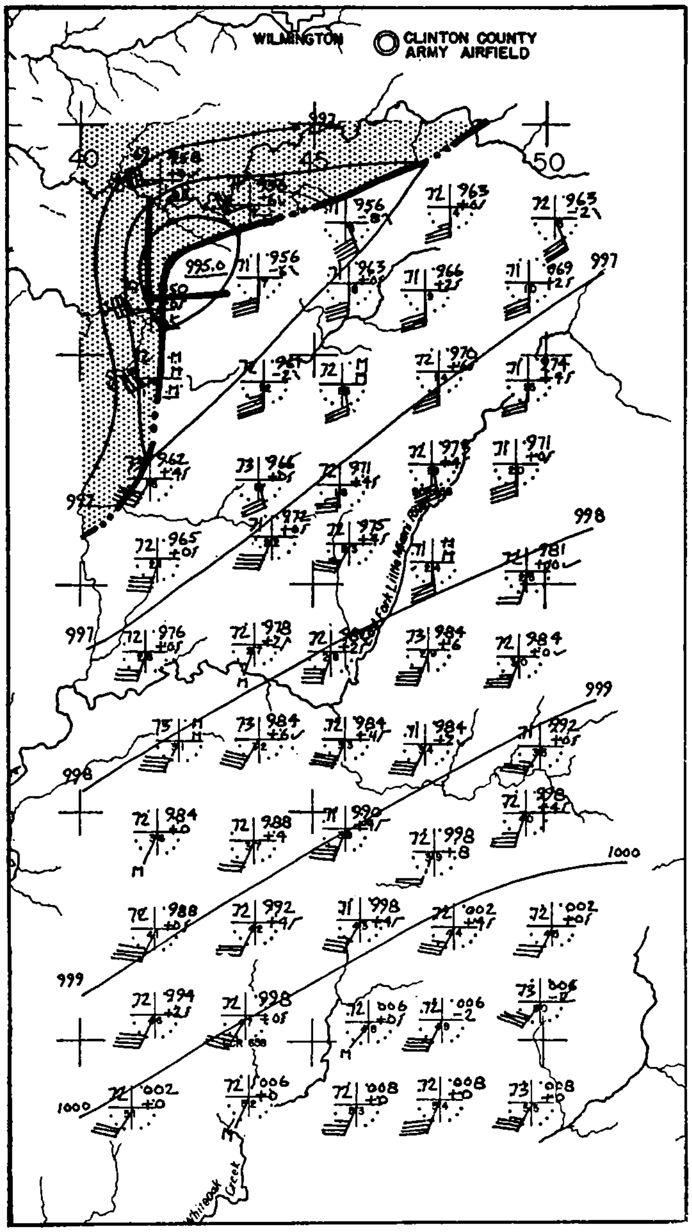

FIGURE 10.—Surface micro-synoptic map for Wilmington Ohio area ,1355 E. S. T., March 19, 1948.

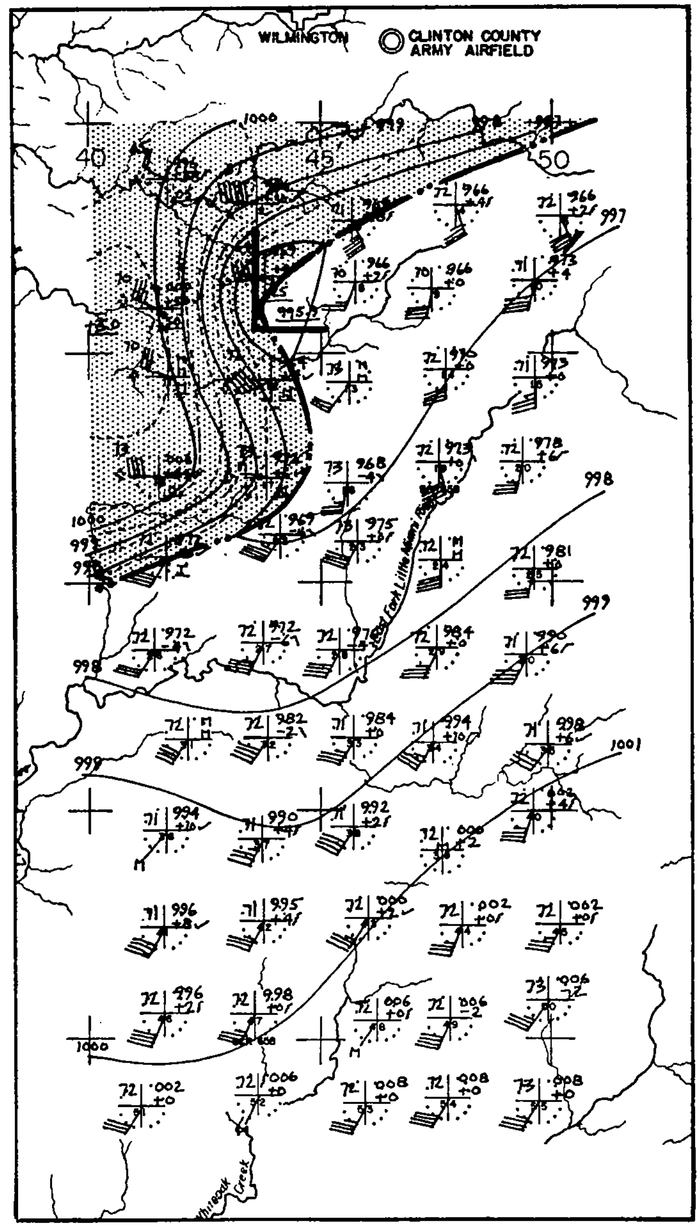

FIGURE 11.—Surface micro-synoptic map for Wilmington Ohio area, 1400 E. S. T., March 19, 1948.

Movement of the squall line.—The average rate of movement of squall lines for the seven cases analyzed was about 40 m. p. h., with the rates for all cases within a range of 35 to 45 m. p. h. Small, very local portions of the lines moved faster or slower than the average. During the storm of March 19, for example, the rate of movement of the micro-wave was about 60 m. p. h. for the period from 1400 to 1405 E. S. T.

The direction from which the squall lines moved averaged west-northwest for six of the seven cases analyzed; it varied within the range of west to northwest. The one case in which the line moved from the south-southwest was not considered a typical example, although no explanation can be given for its unorthodox movement.

Accompanying changes in weather elements.—PRESSURE: Immediately upon the passage of a squall line there was an abrupt rise in pressure. The total rise ranged from 2 to 6 mb., and it sometimes occurred within 5 minutes' time. Local gradients were as steep as 1 to 2 mb. per mile. Correspondingly, isallobaric rises were high, with values as great as 5.6 mb. per 5 minutes recorded. Values such as these are upwards of 50 times greater than those normally encountered in other steep or rapidly changing pressure fields. Following the abrupt rise in pressure, there was a leveling off or a slow falling on the graphs. The configuration resulting on the micro-synoptic map was then a micro-high, or micro-ridge, which rose sharply with the onset of the squall line and sloped gently away 5 to 10 miles behind it.

WIND: In all but one case of the seven analyzed, marked wind shifts occurred upon the squall line's passage. Winds ahead of the lines were usually southerly, and an almost instantaneous shift to westerly or north-westerly winds behind it was observed.

Wind speed remained fairly steady until the passage of the squall line, when a peak gust occurred. This gust lasted for only 1 or 2 minutes and the speed was at times as high as 75 m. p. h., although for the seven cases the peak gusts averaged 56 m. p. h. During the storm of March 19, several stations recorded gusts in excess of 75 m. p. h. Following the peak gust and the passage of the squall line, the wind speed decreased, at first rapidly

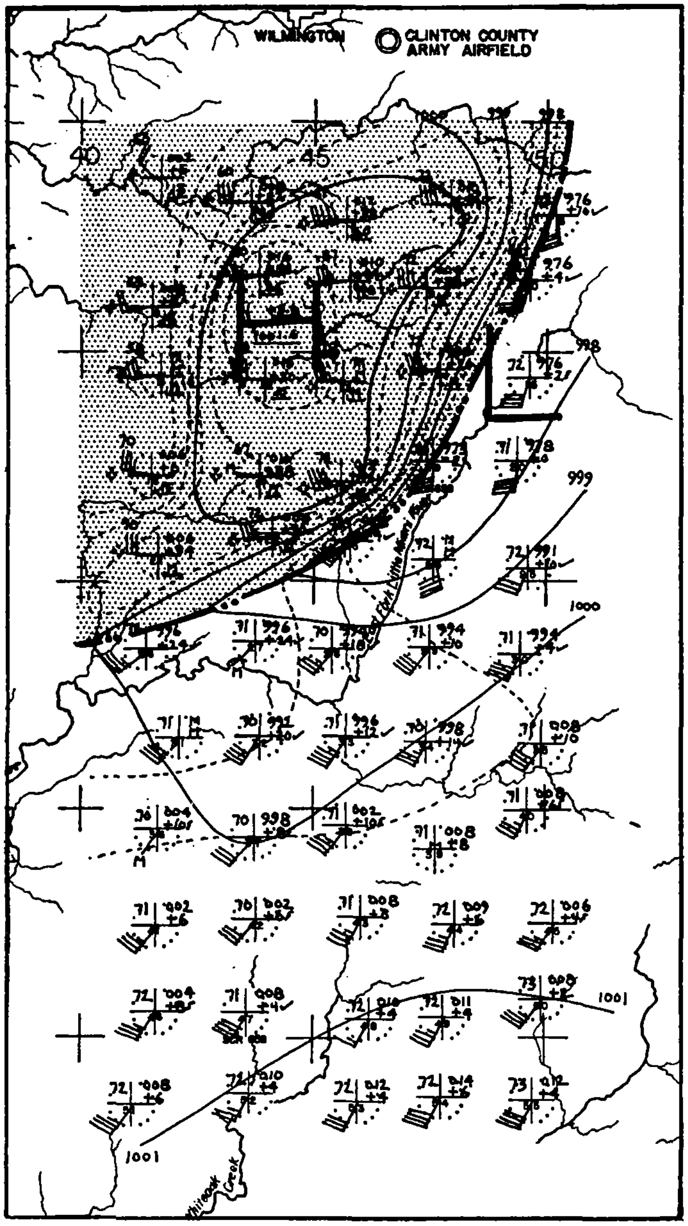

FIGURE 12.—Surface micro-synoptic map for Wilmington Ohio area, 1405 E. S. T., March 19, 1948.

and then more slowly to near its original rate. At the same time the wind direction backed gradually to near its original direction. Ten to twenty miles behind the squall line the wind speed and direction were very much as they had been prior to its passage.

Due to these narrow limitations on the duration of the squall-line wind and to its instantaneous shift, descriptive winds are not often observed at the exact time of the record observations which are plotted on the U. S. synoptic surface map. When an occasional squall-line wind shift is plotted on the map, the analyst frequently disregards it as an "unrepresentative thunderstorm wind." Analysis of these seven cases, however, showed that the wind is highly informative as to the exact position of the line. (Winds associated with a thermal-type thunderstorm do not follow this pattern, so care should be taken in making a map analysis not to confuse a thermal-type thunderstorm with a squall-line thunderstorm; winds of the former blow out in all directions from the storm but do not shift to any particular direction.)

An inspection of the micro-analysis reveals that wind shifts were frequently not as complete as might have been expected from the isobaric pattern. In many cases the flow was at right angles to the isobars. A discussion of the dynamics of this apparent inconsistency is, however, not attempted in this paper.

PRECIPITATION: In each of the seven situations analyzed, precipitation occurred immediately after the onset of the squall line. Small areas of light rain were also present in advance of the squall line in two cases, which may have been due to the proximity of the surface warm front. Rain in the first mile behind the squall line was usually light, becoming severe thereafter. The maximum rate of fall averaged for all seven cases was 0.37 inch per 5 minutes. In one case rain fell at the rate of 0.60 inch for a 5-minute period. Usually the severe rain continued from 10 to 20 minutes and then abated rapidly to moderate or light rain. In most cases, all rain had ceased 45 minutes after the squall-line passage.

Hail occurred with the squall-line passage of March 19, and it was most intense along the path traversed by the micro-wave.

TEMPERATURE: Except for one case, temperatures fell sharply upon the passage of a squall line. (The excepted case was one wherein a surface warm front passed over the network at about the same time.) Maximum drops occurred during the time that severe rain was falling, and usually the amount of the drop was proportional to the rate of rainfall. On an average, temperatures fell 15° F. within 5 or 10 minutes following the squall line's passage, although in one case the drop was 17° F. within 3 minutes' time. With the ending of the period of severe rain, temperatures rose again slowly, frequently returning to near their original levels.

RELATIVE HUMIDITY: Relative humidity values changed inversely with temperature changes, rising sharply to near 100 percent upon the beginning of the rain and falling slowly back to normal when the rain had ended. A more detailed discussion of these and dew point values is not given inasmuch as they were derived from measurements of hair hygrometers which do not give sufficiently accurate measurements for correlation with other data.

CONCLUSIONS

In summarizing the changes in specific surface weather elements accompanying the passage of a squall line, the abruptness, severity, and narrowness characteristic of this zone of activity should be emphasized. This can be brought out by comparing it with any other weather discontinuity; e. g., a surface cold front. If the dome of high pressure following a cold frontal passage be likened to a gently sloping knoll, then the micro-ridge of high pressure following a squall-line passage could be likened to an abrupt, almost vertical cliff. If the knoll be said to cover an area of several thousand square miles then the cliff would, correspondingly, have a width of only a few miles. In fact, the total time covering the passage of the squall line to the return to normal conditions is usually less than 45 minutes. Severe rain is over within 10 to 20 minutes, and all of the rain is over in less than an hour. Wind shifts may last for only 30 minutes, and the peak gust has a duration of only 1 or 2 minutes. Sharp pressure rises are accomplished in 5 or 10 minutes, while pressures may slowly return to normal within an hour. Temperatures fall during the first 5- or 10-minute period and may return to normal within an hour. In general, 1 hour after the squall-line passage conditions may be nearly normal again.

Because of these characteristics, even experienced forecasters have difficulty in locating squall lines when analyzing the synoptic maps by ordinary methods of macro-analysis. Although the presence of all 11 squall lines was evident on the surface synoptic maps of the

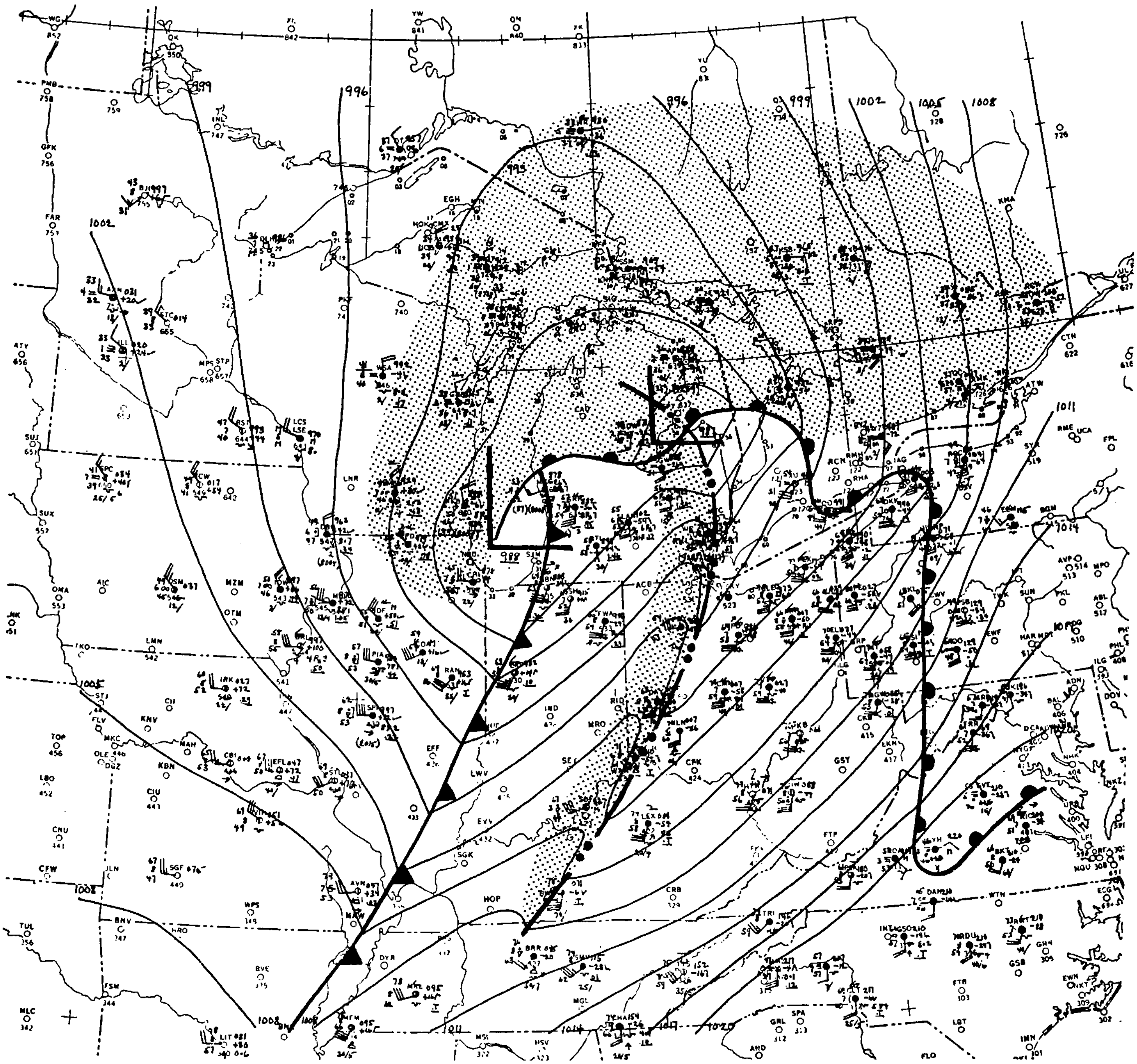

FIGURE 13.—Section of United States surface synoptic map for 1330 E. S. T., March 19, 1948.

United States prepared by the Weather Bureau-Air Force-Navy Analysis Center at Washington, D. C., in a few cases they had been incorrectly located or they were dropped too soon from the maps.

A single observer has even less chance of reporting descriptive weather data for identifying the squall line at any regular 3- or 6-hourly observation. Due to the abruptness of the changes, the more frequent hourly observations may miss the storm. In an exceptional case, when a synoptic observation is taken during a squall-line passage, the data reported by a single observer—especially wind, pressure, and pressure tendency—may appear so confusing to the person analyzing the synoptic map that he does not use the reports. Generally, it may be said that attempting to report or identify a squall-line passage by ordinary methods is like trying to photograph a flying airplane with a time-exposure camera.

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*2. 1948 Surface Observational Data from the Surface Observation Network, U. S. Weather Bureau Cloud Physics Project, Wilmington, Ohio. (Unpublished)

*3. Manuscript Surface Synoptic Charts for 1948, WBAN Analysis Center, U. S. Weather Bureau, Washington, D. C. (Unpublished)

*Information concerning the availability of these data may be obtained from the Scientific Services Division, U. S. Weather Bureau, Washington, D. C.